China and India Lead in Greening of the World through Land-use Management

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Abstract. Green leaves sustain life on Earth by synthesizing sugars from water and carbon dioxide (CO_2) using the energy of sunlight and cool the surface by transpiring large amounts of water during this process. Satellite data reveal increasing green leaf area since the early 1980s due to four factors – one direct (human land-use management) and three indirect (climate change, CO_2 fertilization and nitrogen deposition). However, our analysis of more accurate recent satellite data (2000–2017) reveals a greening pattern that is strikingly prominent in China and India and which overlaps with croplands world-wide. This suggests a more prominent role for the direct factor in greening the world. China alone accounts for 25% of the global net increase in leaf area with only 6.6% of global vegetated area. This equals net greening in the three largest countries, Russia, USA and Canada, that together hold 31% of the global vegetated area. India ranks first amongst all large countries in terms of proportion of vegetated area exhibiting greening and the net increase in leaf area equals that in USA or Canada, each of which has three times more vegetated area. The greening in China is due to forests (42%) and croplands (32%) but in India is mostly from croplands (82%), with negligible contribution from forests (4.4%). China is successfully engineering several ambitious programs to conserve and expand forests with the goal of mitigating land degradation, air pollution and climate change. Already a third of the 2.08 million km^2 of current forests are plantations of growing young trees. Food production in China and India has increased by over 35% since 2000 mostly due to increasing harvested area through multiple cropping facilitated by fertilizer use and surface/ground-water irrigation – which elevates the greenness levels measured from space. Our results show effective human use of land for crops and forests as a key driver of the "Greening Earth", accounting for over a third, and likely more, of the observed net increase in green leaf area. They highlight the need for realistic representation of land-use practices in models and continued monitoring with satellite data.

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1. Leaf Area Change at the Global Scale

- 109.13 million km^2 of global total vegetated area
- A net increase in leaf area of 2.3% per decade
- Adding 5.4×10^6 km^2 new leaf area (2000 to 2017)
- 34.1% (4.9%) of the vegetated area show Greening (Browning). Greening *vs.* Browning is 7:1
- Two-thirds of the increase are contributed by croplands and forests
- The numbered-circled areas highlight the strong greening trends in croplands globally (except circle number 4) , see Fig 1 and Fig 2.
- Clusters still visible when p≤0.05 or p≤0.01

Table 1 | Net changes in leaf area (10^{-1} million km^2) over the period 2000–2017, i.e. the difference between greening and browning.

	Forests	Other woody vegetation	Grasslands	Croplands	All vegetation
Global	16.72	11.50	7.85	17.85	53.91
By latitude					
>50° S/N	4.78	3.48	0.80	2.36	11.41
25° S/N–50° S/N	8.87	3.38	4.61	10.76	27.62
25° S–25° N	3.08	4.64	2.44	4.73	14.88
By mean annual temperature (MAT)					
MAT < 10 °C	7.48	3.61	4.04	5.23	20.36
MAT 10–25 °C	7.92	5.82	2.46	7.70	23.89
MAT > 25 °C	1.32	2.06	1.35	4.92	9.65
By annual total precipitation (ATP)					
ATP < 500 mm	1.76	4.08	3.86	2.66	12.35
ATP 500–1000 mm	7.37	2.29	1.30	9.23	20.20
ATP > 1000 mm	7.59	5.13	2.69	5.95	21.35

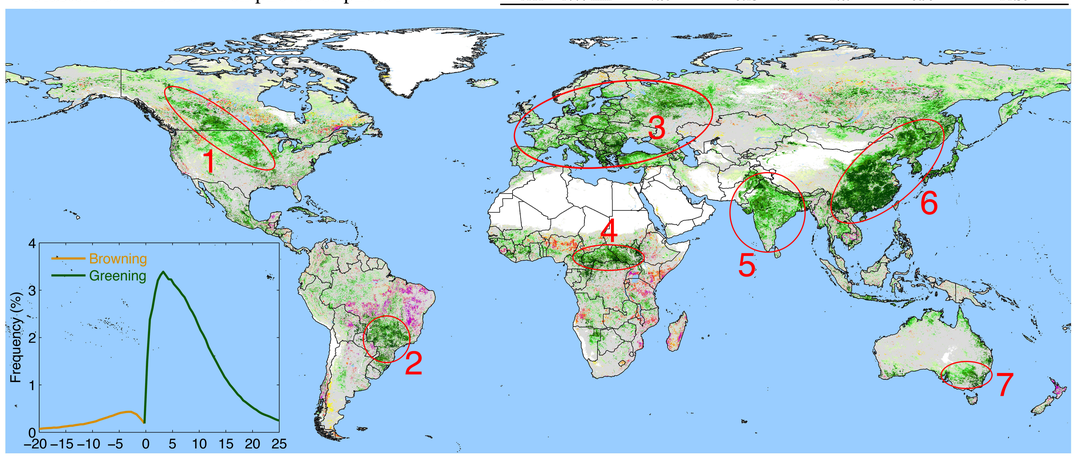

Fig. 1 | a. Map of trends (p≤0.1) in annual average MODIS LAI over 2000–2017. The inset shows the frequency distribution of statistically significant trends.

2. A Dominant Role of Direct driver – Human Land-use Management

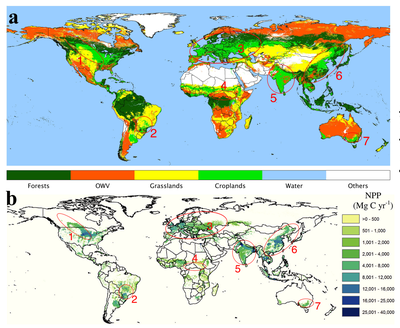

Fig. 2 | a. Map of broad vegetation classes. **b.** Map of agricultural Net Primary Production (NPP) in year 2009 (screenshot of Fig.3 in Wolf et al., 2015).

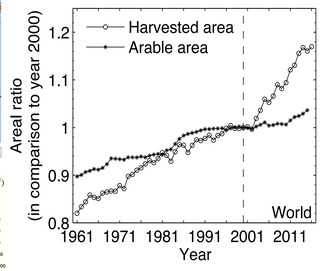

Fig. 3 | Ratio of harvested area and arable area with respect to year 2000 year values.

❑ Green revolution

- Croplands contributes the most (33%) to the global greening since 2000
- Six of the seven clusters overlap
- Quick-growing hybrid cultivars
- Multiple cropping
- Irrigation and fertilizer
- Pest control
- Better-quality seeds
- Farm mechanisation
- Credit availability
- Crop insurance programs
- Production increase in northern temperate regions

❑ CO_2 fertilization is not as prominent as expected in hot and arid environments

- Greening of natural vegetation from these regions contributes much less than those from mild and wet climates (Table 1)
- (MAT > 25 °C, 13%) *vs.* (MAT < 25 °C, 87%)
- (ATP <500 mm, 27%) *vs.* (ATP > 500 mm, 73%)
- Also true when adjusted by vegetated area

❑ Forests in the northern hemisphere

- Plantations in China
- Silviculture practices in developed countries
- Selected logging in Europe

3. Rankings for Countries

❑ China and India stand out

- Over 65% of the vegetated lands show greening
- China alone accounts for 25% of the global net increase in leaf area with only 6.6% of the global vegetated area => sum of greening in (Russia + USA + Canada)
- India ranks first in the proportion of vegetated area exhibiting greening (69%), with only 2.7% of the global vegetated, India accounts for 6.8% of global greening => greening in USA or Canada

❑ Europe Union, Brazil and USA

- EU ranks 3rd in net leaf area increase - 55% of which is due to croplands and 34% to forests
- Brazil ranks towards the bottom because greening from croplands and pastures is offset by browning in forests and cerrado.
- USA ranks in the middle but noticeable contribution from croplands

Table 2 | Ranking of eleven largest countries by vegetated land area and proportion of vegetated lands showing statistically significant trends.

Rank	Vegetated land area (million km^2)	Proportion of vegetated lands showing greening (%)	Proportion of vegetated lands showing browning (%)
1	Russia (16.04)	India (69.0)	Brazil (11.6)
2	USA (8.91)	China (65.6)	Indonesia (6.8)
3	Canada (8.47)	EU* (51.4)	Argentina (6.7)
4	Brazil (8.31)	Canada (41.6)	Canada (5.7)
5	Australia (7.50)	Russia (38.0)	D. R. Congo (4.5)
6	China (7.19)	USA (33.3)	USA (2.9)
7	EU* (4.22)	Mexico (28.4)	Russia (2.7)
8	India (2.94)	Brazil (25.6)	Mexico (2.4)
9	Argentina (2.57)	Australia (24.4)	China (1.3)
10	D. R. Congo (2.28)	D. R. Congo (23.7)	EU* (1.3)
11	Mexico (1.88)	Indonesia (19.7)	Australia (0.8)
12	Indonesia (1.80)	Argentina (13.2)	India (0.8)

Table 3 | Ranking of eleven largest countries by leaf area and its change during 2000–2017.

Rank	Annual average leaf area in 2000 (million km^2)	Net change in leaf area (10^{-1} million km^2)	Net change in leaf area (%)
1	Brazil (29.68)	China (13.51)	China (17.80)
2	Russia (12.36)	Russia (7.57)	India (11.10)
3	USA (8.93)	EU* (4.02)	EU* (7.78)
4	Indonesia (8.69)	India (3.65)	Canada (7.13)
5	D. R. Congo (8.50)	USA (3.59)	Russia (6.62)
6	China (7.64)	Canada (3.35)	Australia (5.62)
7	Canada (5.41)	Australia (2.83)	USA (4.55)
8	EU* (5.23)	Brazil (1.12)	Mexico (4.07)
9	Australia (5.19)	Mexico (0.96)	Argentina (1.70)
10	India (3.33)	D. R. Congo (0.96)	Brazil (1.54)
11	Mexico (2.66)	Indonesia (0.51)	D. R. Congo (1.34)
12	Argentina (2.16)	Argentina (0.13)	Indonesia (0.83)

4. What Explains the Large-scale Greening of China and India

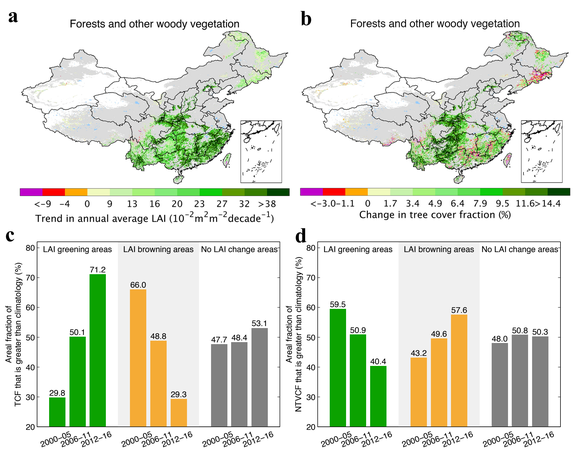

Fig. 4 |Trends in forests and other woody vegetation of China. a, Trend in annual average LAI. **b**, Change in tree cover fraction between 2014–16 and 2000–02 over areas showing statistically significant LAI trends in (**a**). **c**, **d**, Areal fraction of tree cover fraction (TCF) (**c**) and non-tree vegetation cover fraction (NTVCF) (**d**) over forests and other woody vegetation that is greater than the climatology during a particular period, i.e., 2000–05, 2006–11, and 2012–16. The colors further confine the analysis to LAI greening (green bars), browning (browning bars) and no LAI change (grey bars) areas.

❑ China forests

- Forests contribute 42 % of net increase in leaf area
- Croplands contributes 32% of net increase in leaf area
- 84% of all forests and other wooded land show greening
- Less than 1% of such show browning
- Increase (decrease) in tree (non-tree) cover in the greening areas
- Inventory data shows 19% increase in forest area
- A third of current forest are plantations with rapid growing young trees
- The mean LAI trend (0.23 m^2 m^{-2} decade^{-1}) for regions with Planted Forest Fraction (PFF) ≥ 10% is 53% greater than the mean LAI trend (0.15 m^2 m^{-2} decade^{-1}) for regions with PFF < 10%.
- The mean tree cover trend (6.18 % decade^{-1}) for regions with PFF ≥ 10% is 29% greater than the mean tree cover trend (4.90 % decade^{-1}) for regions with PFF < 10%.

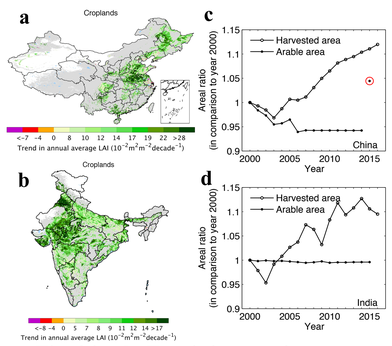

Fig. 3 | a, **b**, Trends in annual average LAI over croplands in China (**a**) and India (**b**). **c–d**, Ratio of harvested area (circle) and arable area (asterisk) with respect to year 2000 values for China (**c**), India (**d**).

❑ China and India croplands

- Contributes 32% (China) and 82% (India) to the net increase in leaf area
- FAO statistics show food production has increased 35% to 40%
- China cereal production: 407×10^6 tonnes in 2000 vs. 583×10^6 tonnes in 2006
- India cereal production: 235×10^6 tonnes in 2000 vs. 295×10^6 tonnes in 2006
- Significant increase in harvested area through multiple cropping
- Brazil is also noteworthy but starting from lower base values

5. Conclusions

- Effective human use of land for crops and forests is a key driver of the "Greening Earth", accounting for over a third, and likely more, of the observed net increase in green leaf area.
- They highlight the need for realistic representation of land-use practices in models and continued monitoring with satellite data.